SECTION 8.0
MONITORING THE PERFORMANCE OF A PERMEABLE BARRIER

Once the permeable barrier has been designed and installed, the system will have to be monitored as long as the plume exists. Monitoring is done to achieve the following objectives:

- Ensure that the plume is being adequately captured and treated. Also, it is important to analyze the downgradient aquifer water to determine if the barrier has had any adverse effects on groundwater quality. The type and frequency of monitoring required to achieve this objective are usually decided during discussions between the site manager and the regulators. The monitoring for this objective falls into the category of compliance monitoring required to ensure human health risk reduction and environmental protection.

- Determine how well the installed barrier meets design specifications. During the early stages of operations, the site manager will be able to determine causes for the potential success or failure of the barrier.

- Estimate the longevity of the barrier. Over the long term, the site manager will be able to anticipate potential maintenance activities and costs.

8.1 ADEQUACY OF PLUME CAPTURE AND TREATMENT

After installation of the permeable barrier is complete, the site manager and regulators will need to know if the plume is being adequately captured and treated. From a compliance perspective, the monitoring is done to ensure that downgradient contaminant concentrations are below target cleanup levels. This involves looking for three things:

- Potential breakthrough of contaminants or environmentally deleterious byproducts through the reactive cell

- Potential contaminant bypass around or beneath the barrier

- Potentially deleterious effects on groundwater quality due to the barrier itself.

8.1.1 Monitoring for Potential Breakthrough or Bypass of Contaminants

The type and frequency of monitoring required to achieve this critical objective are likely to be very site specific, although the ITRC Permeable Barriers Subgroup is trying to formulate guidelines for monitoring such installations. Figure 8-1 shows examples of monitoring well configurations that could be used, depending on site conditions, to monitor for breakthrough and bypass of contaminants. In Figure 8-1a, monitoring is done along the downgradient edge of the reactive cell using a row of long-screened wells. If the contaminant distribution in the plume is particularly heterogeneous with respect to depth, well clusters may be used instead of long-screen wells. Well screens are placed so as to exclude 1 foot at the top and bottom. Wells are placed a few inches inside the reactive medium rather than in the pea gravel (as in Figure 8-lb) because the pea gravel may contain some stagnant water entering from the downgradient formation. This is a concern especially if the barrier is built within the plume. Placing the monitoring wells within the reactive medium also provides a level of safety. If contaminant breakthrough is observed in these wells, there is still some reactive medium that can treat the contaminants

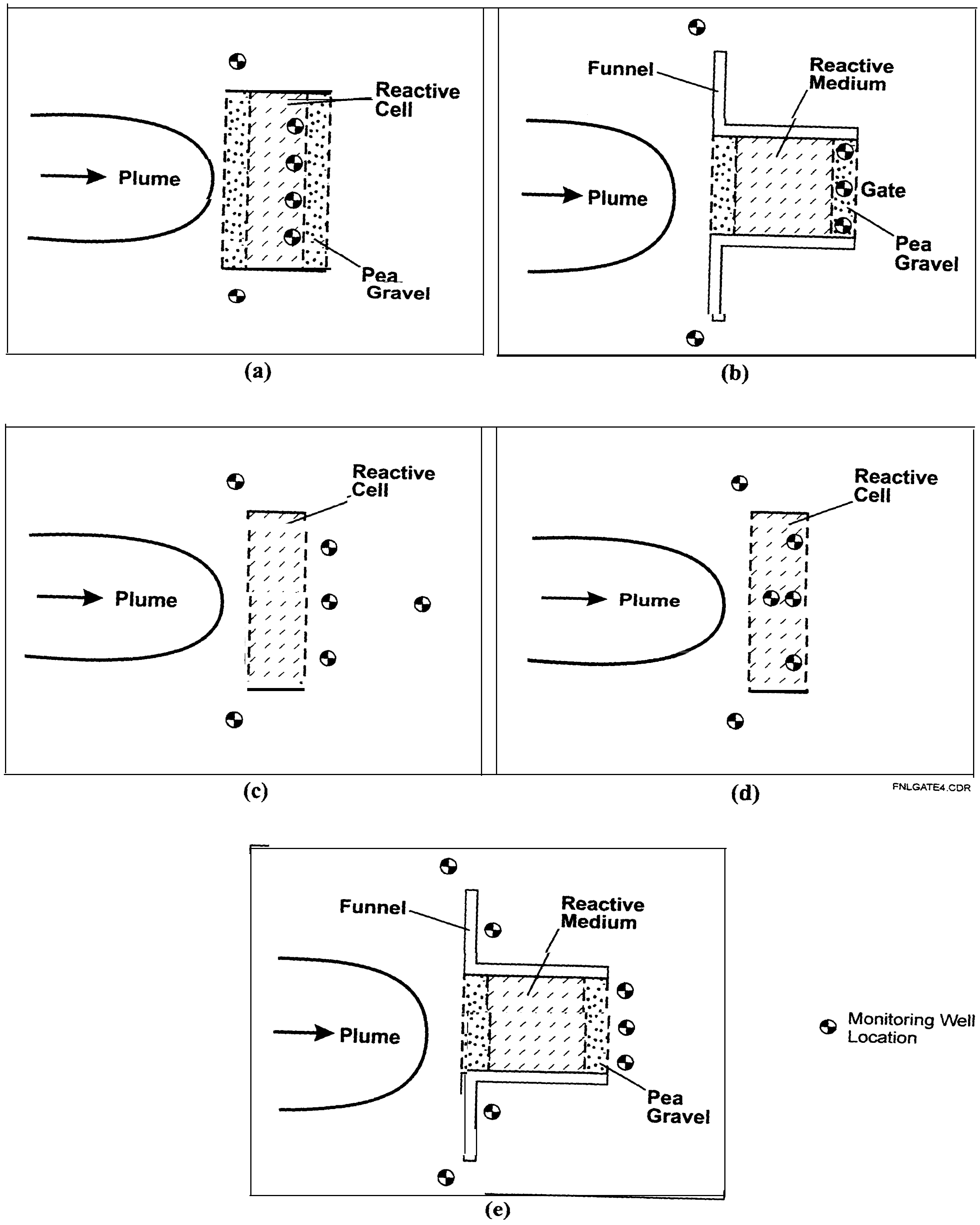

Figure 8-1. Various Monitoring Well Configurations for Evaluating Performance of the Barrier

further before the groundwater exits the reactive cell. Additional monitoring wells are placed at the two ends of the barrier to monitor for contaminant bypass that could result from inadequate flow capture.

Figure 8-1c shows another possible arrangement of monitoring wells. In this arrangement, monitoring wells are placed in the downgradient aquifer instead of in the reactive cell or pea gravel. If there is potential for flow bypass beneath or around the barrier, this arrangement could provide more information. Flow bypass beneath the barrier would occur if the barrier is not properly keyed into the aquitard or if the aquitard itself has fractures. Flow bypass around the barrier could take place if the actual hydraulic capture zone becomes smaller than designed or if the plume shape changes over time. Downgradient water quality could be monitored over increasing distances from the barrier to evaluate flow remixing and geochemical parameter rebound.

The required frequency of compliance monitoring will be determined during discussions with the regulators. Quarterly monitoring is usually required at contaminated sites. In general, the monitoring frequency for permeable barrier installations is not expected to be very high. As seen in Section 2, unless the dissolved oxygen content of the groundwater and the flow velocity through the reactive cell are both very high, the reactive medium is consumed slowly, over a time scale of years. One safety measure would be to install another row of monitoring wells within the reactive cell at about 1 foot from the downgradient edge (see Figure 8-1d). Because the design of the reactive cell usually involves safety factors that provide for additional reactive cell thickness, this row of wells would serve as an early indicator of impending breakthrough. Figure 8-2 shows the results of monitoring conducted in several wells along the center line through the reactive cell in the direction of groundwater flow at a pilot barrier in California (Battelle, 1997). Levels C and D in this figure indicate different depths in the monitoring well cluster at each location. The slight rebound in contaminant concentrations in the downgradient pea gravel probably indicates some residual contamination entering from the downgradient formation (aquifer). This pilot barrier is placed in the middle of a TCE plume. Figure 8-2 also shows the reason why downgradient monitoring wells may need to be placed within the reactive cell rather than in the downgradient pea gravel.

It has been assumed that no contaminant transport occurs through the funnel walls. If there is some uncertainty regarding the impermeability of the funnel, either because of geotechnical difficulties during installation or because innovative emplacement methods were used, additional wells could be installed immediately downgradient from the funnel (see Figure 8-1e) to monitor for breakthrough.

Because monitoring costs will probably constitute the major operating cost of the barrier over the next several years, site managers will wish to optimize the number of monitoring wells and the information gained. Adequate site characterization in the vicinity of the proposed permeable barrier location, as well as hydrologic and geochemical modeling, can assist both site managers and regulators to determine the appropriate number of monitoring wells at a given site and their locations.

Monitoring wells within the reactive cell can be either long-screen wells (for homogeneous flow) or cluster wells (for heterogeneous flow). It should be noted that, although there is homogeneous flow in the aquifer, there may be heterogeneous flow in the reactive cell depending on how well the granular reactive medium has consolidated. The monitoring wells may be constructed using 1- or 2-inch-diameter PVC casing. The diameter of monitoring wells is determined based on the space available in the reactive cell and the size of the measuring instruments that will be inserted during monitoring. The wells may be installed prior to placing the granular medium in the trench, and may be supported by metal frames, which are removed as the trench is filled. Figure 8-3 shows monitoring wells being installed in two types of reactive cells. Figure 8-3a shows monitoring wells supported in a trench-type reactive cell.

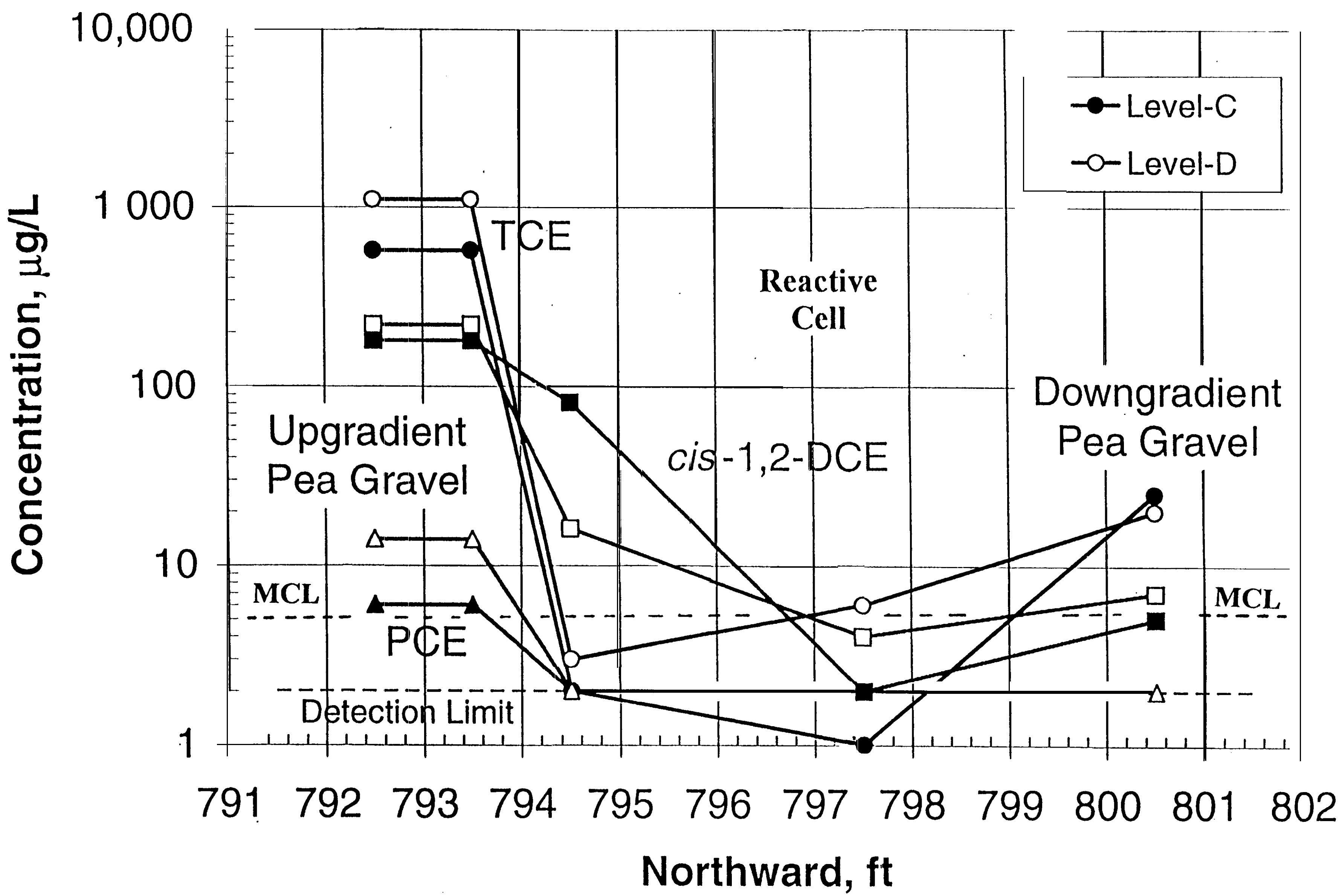

Figure 8-2. Concentrations of Chlorinated Compounds Along Center Line in the Flowpath of Existing Permeable Barrier (Battelle, 997)

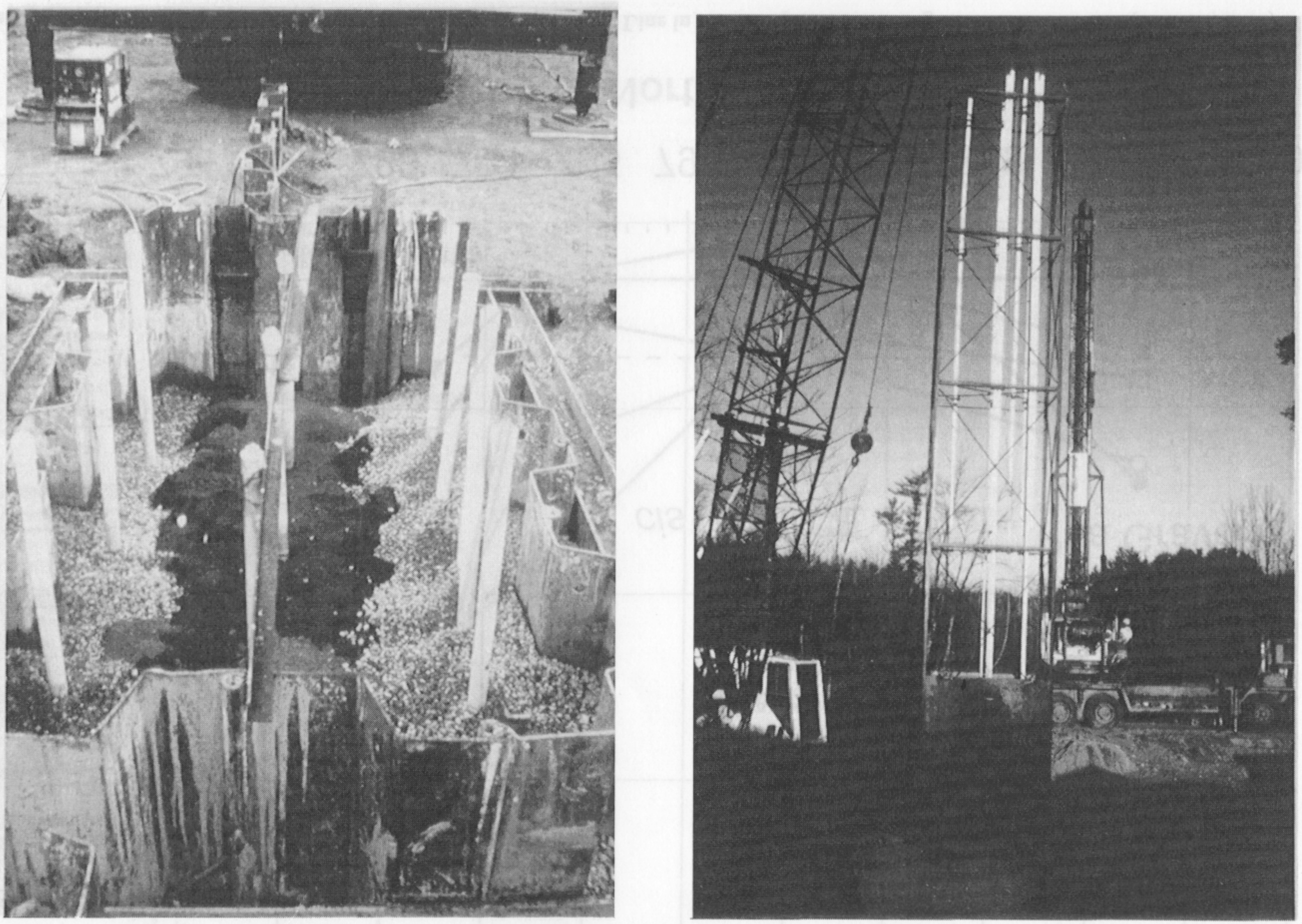

Figure 8-3. Installation of Monitoring Wells in the Reactive Cell and Pea Gravel (Source: ETI, 1997)
(left) Trench-Type Emplacement **(right) Caisson-Based Emplacement**

Figure 8-3b shows monitoring wells supported by a frame being installed in a caisson-based excavation. If an in situ groundwater velocity meter is to be used, it would have to be similarly installed during construction of the reactive cell (see Section 8.2.1).

8.1.2 Sampling and Analysis for Contaminants and Byproducts

The chemical parameters that are typically measured in the monitoring wells include concentrations of contaminants (e.g., TCE, PCE, etc.) and potential toxic byproducts (e.g., *cis*-1,2-DCE, VC, etc.). Sampling and analytical techniques for monitoring wells located in the aquifer are similar to those described in Section 3 for site characterization. However, special precautions may be required while sampling monitoring wells located within the reactive cell or pea gravel.

When collecting groundwater samples from the reactive cell or pea gravel, traditional methods involving purging several casing or pore volumes of water prior to collection should be avoided. Such practices may capture water that represents a significantly lower residence time in the reactive cell. Rapid withdrawal of a water sample by any sampling method may draw water quickly from the upgradient direction, and such water may have been incompletely treated by the reactive medium. Analyzing a mixture of water from locations partially outside of the monitoring well screen could suggest higher levels of the target analytes than actually exist. Alternative sampling methods that are expected to yield more representative water samples in a permeable barrier have been discussed by Warner et al. (1996) and Kearl et al. (1994). Examples of potentially favorable groundwater sampling techniques include the following:

- Purge small volumes of casing water (micropurging) before collecting the sample. Water is extracted at very low rates for both purging and sampling to minimize disturbance of the pore water. This prevents groundwater that has not had sufficient residence time from being drawn into the sample.
- Use packers to isolate nonrepresentative casing water from the flow system.
- Sample symmetrically along the flow direction to avoid setting up artificial gradients.
- Progressively remove samples from the downgradient direction toward the upgradient direction to minimize potential cross-contamination by the sampling equipment.

Before any groundwater sampling is done it is essential to develop a Quality Assurance Project Plan (QAPP) that addresses the QA requirements of the investigation. U.S. EPA's *Pocket Guide for the Preparation of Quality Assurance Project Plans* (EPA/600/9-89/087) is a useful resource for preparing a QAPP. U.S. EPA utilizes a four-tiered project category system with Category I being the most stringent and Category IV being the least stringent. Category I plans are for projects that are of sufficient scope and substance that their results could be used directly, without additional support, for compliance or other litigation. Because such projects are intended to withstand legal challenge, Category I QA requirements are the most rigorous and detailed. Category II plans are for projects that are of sufficient scope and substance that their results could be combined with the results of other projects of similar scope to produce narratives that would be used for rulemaking, regulation making, or policy making. Other projects that do not fit these criteria, but have high visibility, would be included in this category. Category III plans are for projects that produce results that will be used for evaluating and selecting basic options, or performing feasibility studies. Most treatability studies and field pilot barriers would be evaluated in Category III. Category IV plans are the least stringent.

8.1.3 Monitoring Downgradient Water Quality

In addition to monitoring for breakthrough or bypass of target contaminants (and potential toxic byproducts), it is important to monitor downgradient aquifer wells for potentially undesirable characteristics, due to secondary effects of the barrier. Depending on the site geology and geochemistry, some water quality parameters that may be affected by the barrier are soluble iron (primarily ferrous), hardness (calcium, magnesium, and alkalinity), sulfate, DO, pH, and Eh. High levels of soluble iron are undesirable from a water quality perspective, because of staining that can be caused by oxidation of the ferrous iron after the water is exposed to atmospheric air. However, high soluble iron concentrations can occur only in acidic or anoxic groundwaters. In neutral to slightly alkaline water with DO above 0.01%, most available iron will oxidize to ferric species and precipitate as a very-low-solubility solid. Generally, hard water will diminish in hardness due to precipitation of calcium and magnesium carbonates within the reactive cell. However, water hardness usually is not considered to be a critical water quality parameter. If sulfur-reducing microorganisms are present, the sulfate concentration may decline due to reduction to sulfide (bisulfide) and precipitate as FeS or other low-solubility solids. In most cases, water exiting the reactive cell will have negligible DO, moderately alkaline pH (typically 8 to 11), and low Eh (< O). However, these parameters may be quickly restored to their original values upgradient of the barrier by reaction with soil minerals and air exchange with the atmosphere. At sites with a low air permeability cover, such as pavement on the ground surface, DO concentrations may remain low, thus favoring iron solubility.

8.2 DETERMINING IF THE BARRIER MEETS DESIGN SPECIFICATIONS

A monitoring plan may be needed to determine if the barrier meets design specifications. In the short term, if the barrier is not performing according to design goals, additional monitoring can help the site manager identify the reasons. Several different monitoring activities and tests can be conducted to evaluate this objective at the discretion of the site manager:

- Estimating residence times in the reactive cell. This generally involves measurement of the groundwater velocity or hydraulic conductivity distribution in the reactive cell.

- Estimating hydraulic capture zone. This generally involves taking water-level measurements in wells upgradient of the permeable barrier.

8.2.1 Estimating Residence Time Distribution in the Reactive Cell

Degradation of halogenated hydrocarbons is controlled by rate-dependent processes taking place in the reactive cell. Therefore, residence times (the amount of time that the water is in contact with the reactive medium) affect the degree to which susceptible groundwater contaminants are degraded. Groundwater flow velocity measurements within the reactive cell provide information pertaining to residence time. In-well or in situ flowmeters may be used to monitor for spatial or temporal changes in flow velocity (Ballard, 1996). In-well groundwater velocity probes can be inserted in 2-inch or larger monitoring wells. One probe can be used to take measurements from several wells. The in situ velocity meter, on the other hand, is generally installed in the center of the reactive cell and stays there to provide a 3-D groundwater velocity vector for about 1 year. The in situ meter provides an average velocity measurement in a 1-m^3 region.

Residence time is actually a range rather than a single time because of potential heterogeneity within the barrier. Heterogeneity can decrease the overall effectiveness of the reactive cell by accelerating flow at preferential locations within the cell and thus decrease contact time between the groundwater and reactive medium. Heterogeneity increases hydrodynamic dispersion, which can promote breakthrough of contaminants. Heterogeneous flow can be caused by several factors, such as differential compaction of the iron fines, development of corrosion products on reactive medium surfaces (hydrous oxides), and precipitation of secondary minerals in the interstitial pore space (e.g., calcite, siderite, brucite). Any evidence in the breakthrough of primary organic contaminants or byproducts may indicate development of heterogeneity.

Because heterogeneities can develop within the reactive cell, it is necessary to monitor for indications of chemical changes within the cell. Chemical changes can be monitored by measuring the concentrations of contaminants and native inorganic constituents (e.g., Ca, Mg, alkalinity) in monitoring wells within the reactive cell and the surrounding regions. Monitoring of the field parameters pH, Eh, and DO is very important because they can be used to determine whether conditions are conducive to the formation of inorganic precipitates. In addition, these field parameters indicate whether conditions in the cell are optimal for reductive dechlorination to occur.

Tracer tests with a conservative tracer can be used to evaluate potential heterogeneities in the reactive cell. Sodium bromide has been found to work well in an iron reactive medium when a retardation factor of 1.2 is incorporated (Sivavec, 1996; ETI, 1996). During preliminary site characterization, the levels of bromide in the native groundwater should be measured. Elevated levels of bromide in the native groundwater would make the tracer test more difficult, because a larger concentration of sodium bromide tracer would be required. At high concentrations (greater than 1 percent), bromide may be subject to a density gradient as it travels through the aquifer or reactive cell. The resulting path of the tracer, then, may not be the same as that of the organic contaminants. One advantage of a bromide tracer is its ability to be continuously monitored using downhole, ion-selective electrodes. Continuous monitoring with such probes increases the probability of capturing the tracer peak and reduces labor costs. Ion-selective probes are expensive, but their cost could be justified by reduced labor requirements and increased chances of success. Field application of tracer tests for evaluating permeable barriers has not been very successful in the past due to a variety of reasons (Focht et al., 1997). Difficulties in ensuring the success of tracer tests occur due to the high cost involved in obtaining adequate sampling density (number of monitoring wells) and to the limitations of monitoring instruments. Other, possibly less expensive, methods of determining heterogeneities and conductivity distribution include the use of in-hole groundwater velocity probes, slug tests, and pump tests in the reactive cell. The in-hole or in situ velocity meters, especially, hold a lot of promise.

8.2.2 Estimating the Hydraulic Capture Zone Size

The size of the hydraulic capture zone is another important criterion for meeting design specifications. The permeable barrier system is designed to capture the plume and direct it through the reactive cell. This activity evaluates how well the capture is being achieved on the upgradient side of the barrier. In simulated homogeneous and isotropic aquifers, groundwater modeling studies have shown that the capture zones are symmetrical and that their size is based on the permeability contrast between the reactive cell and the aquifer medium (Starr and Cherry, 1994). However, as discussed in Section 5.1, the groundwater flow modeling at a heterogeneous site (Battelle, 1996c) showed that subsurface channels cause the capture zones to be substantially asymmetrical, both laterally and vertically. This example illustrates the dependence of capture zones on aquifer heterogeneities and the need for detailed site characterization prior to permeable barrier placement. This can aid in designing an appropriate monitoring scheme for estimating the capture zone size through field measurements and modeling.

The predictions made through groundwater modeling can be validated by field determination of the capture zones and flow field in the immediate vicinity of the permeable cell system. Insight gained through field observations can be useful in evaluating the design configuration of the permeable cell. This information may be useful also in cases where a pilot-scale permeable cell will be upgraded to a full-scale system in the future. The contribution of the funnel walls in increasing the flow through the gate also can be evaluated. The following activities can be conducted to evaluate the hydraulic capture zone size:

- Install several monitoring points upgradient of the wall. Figure 8-4 shows an example of a monitoring well arrangement that could be used to evaluate the hydraulic capture zone width. The water-level data from these wells should be used to determine the groundwater flow field. In addition, the borehole logs from these wells can be used to enhance site characterization with data regarding aquifer heterogeneities.

- Perform slug tests in upgradient wells to determine the K distribution in the aquifer and to support any detailed capture zone models.

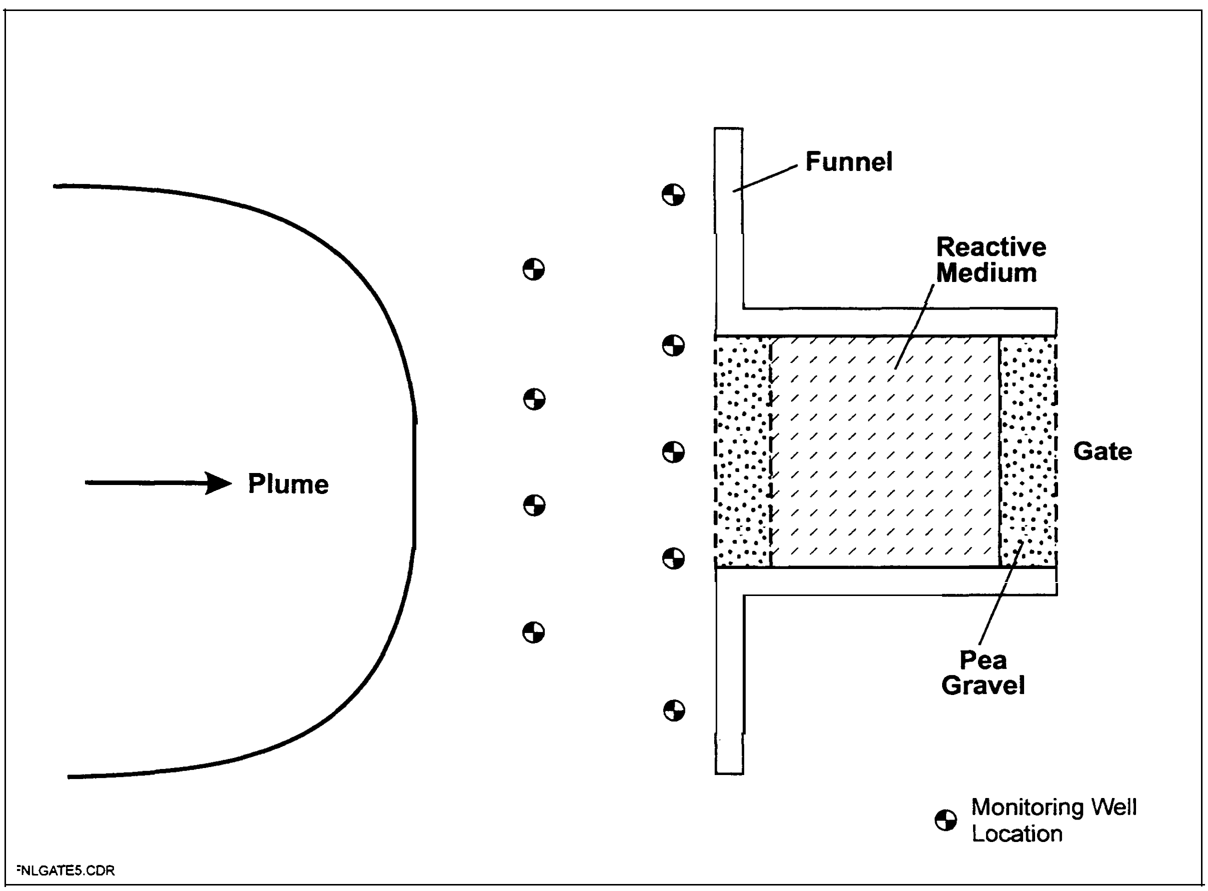

Figure 8-4. Possible Monitoring Well Configurations to Evaluate Hydraulic Capture Zone

- Perform tracer tests upgradient of the permeable barrier to determine flowpaths, capture zones, and flow velocities and to validate the model predictions. A relatively conservative tracer such as bromide may be used.

Tracer tests are difficult to conduct successfully without installing a large number of wells. Even wells as close as 5 feet apart can miss the tracer peak as it passes through. In addition, if the groundwater velocity at the site is very slow, it may take a long time (and higher costs) to conduct each tracer injection test.

8.3 ESTIMATING THE LONGEVITY OF THE BARRIER

The reactive cell causes dechlorination of groundwater contaminants by a reduction process in which the iron metal is consumed and iron oxide compounds are formed. As these and other compounds precipitate on the reactive metal surfaces, the reactive cell may become less effective in capturing and treating contaminated groundwater. It is of interest to determine how performance will be affected over time and to understand exactly what processes are responsible for a decline in performance. In addition, it is important to be able to predict how long the reactive cell will remain useful, both for planning purposes and to annualize cost. Some methods that may be used to assess whether barrier performance is deteriorating are as follows:

- Comparison of time series measurements of groundwater and hydrologic parameters
- Analysis of core samples within the reactive cell.

The techniques described in Section 8.1 to monitor breakthrough of contaminants and byproducts during each sampling round can be applied during multiple sampling events to determine whether performance of the reactive cell is changing over time. To determine whether temporal changes occur, groundwater samples should be collected from the same monitoring wells at regular intervals during the entire course of the evaluation. The data collected could be subjected to statistical techniques to determine whether variations are time-dependent or are random fluctuations. In addition, the ratio of concentrations in two wells in a particular flowpath may be tracked over time. Any consistent increase in the ratio of the upgradient well concentrations to the downgradient well concentrations would indicate a loss in performance. If any of the data represent time-dependent variables, it would be useful to extract rate information about the variables. Rate information could be extrapolated to predict the useful lifetime of the cell.

It is expected that the cell's peak performance will occur when the reactive metal particles are still relatively new and few mineral precipitates have deposited in the interstitial pore space. As the reactive medium oxidizes (corrodes) and the pore spaces become clogged by mineral precipitates, the performance of the reactive cell should decline. To better understand the processes that affect the longevity of the cell it is desirable to periodically monitor groundwater parameters that are related to changes in performance. Some key groundwater parameters that should be monitored are pH, Eh, and DO. Similarly, chemical species that may react in the cell include Ca, Fe, Mg, Mn, Al, Ba, Cl, F, SO_4^{2-} and HCO_3^- (alkalinity); significant redox-sensitive elements include Fe, C, S, and N.

Geochemical modeling codes (see Section 6.2) can be used to evaluate the potential for precipitation in the reactive cell. Inverse modeling codes are especially suited for evaluating probable reactions in the reactive cell, given the concentrations of the various chemical species observed in upgradient and downgradient monitoring wells (before and after the reactive cell). Even in the absence of computerized modeling, just an arithmetical comparison of parameters, such as Ca and Mg, before and after the reactive cell can provide a valuable indication of potential reactive cell reactions.

If there are indications of a loss in performance due to precipitation, a few core samples taken from within the reactive cell can be evaluated. The cores could be taken in a vertical direction from the first few inches in the upgradient section, from the middle, and from the last few inches in the down-gradient section of the cell to get adequate spatial information about possible changes in the reactive medium. A horizontal core through the upgradient pea gravel-reactive cell interface also could be collected to provide information on front-end corrosion of the iron due to DO in the groundwater. It will be necessary to prevent oxygen from contacting the cores prior to analysis. The boreholes could be backfilled with fresh reactive medium to restore the integrity of the cell.

Optical microscopy can be performed for visual inspection of the core samples. Microscope imaging techniques can be applied to characterize the iron oxide coatings, mineral precipitates, and any other particulate matter. Scanning electron microscopy (SEM) can be used if the benefits of backscatter electron images and elemental mapping are needed. In addition, the elemental composition can be determined by energy-dispersive x-ray spectroscopy (EDS) using an SEM, or by wave-dispersive spectroscopy (WDS) using an electron microprobe. Powder x-ray diffraction (XRD) techniques can be used to identify mineral precipitates by their crystal structures. Because iron hydroxides formed at low temperatures tend to be amorphous, they may not be detectable by XRD. If necessary, the particle number and particle-size distribution (dimensional area, and aspect ratio) can be determined using an imaging system interfaced to an optical or electron microscope. The core samples also can be evaluated for biological growth (see Appendix A-3).

The hydraulic capture volume of the permeable barrier might decrease if the hydraulic conductivity of the reactive cell is reduced due to precipitate or bacterial buildup on the reactive medium. The following activities could be conducted to evaluate changes in the hydraulic performance of the barrier over time:

- Conduct hydrogeologic modeling to develop cause-effect scenarios including the effect of lower reactive cell conductivity on the capture zones, shift in flow divides, and change in flow volumes.

- Monitor the water levels periodically in all wells and continuously in a few wells to determine and interpret any changes in water levels over time. It is expected that any significant decrease in reactive-cell conductivity will cause a water-level buildup upgradient of the cell. The water-level data also can be used to determine any changes in flow fields over time.

- If a significant change in water levels and flow patterns over time is observed, conduct slug tests within the reactive cell to determine whether the water-level changes are related to a decrease in hydraulic conductivity of the reactive cell. It is possible that the high conductivity of the reactive medium in the early stages of monitoring will result in extremely high response times during slug tests. Therefore, care should be exercised to record water-level changes at the highest possible frequency of the data loggers.

- If significant changes in water levels and conductivity are observed, the tracer test could be repeated upgradient of the cell to evaluate the effect on the capture zone and flow velocities. However, tracer tests are difficult to conduct and water-level measurements in upgradient wells may still provide a reasonably good estimate of the capture zone.